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REAL-TIME FREQUENCY ANALYSIS METHODOLOGY FOR EVOKED POTENTIAL LOOP-CLOSURE (U)

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

William T. Watson

for **KENNETH R. BOFF**, Chief
Human Engineering Division
Armstrong Laboratory

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Real Time Frequency Analysis Methodology for Evoked Potential Loop-Closure

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Evoked EEG response research indicates the potential for a usable brain actuated control system. Reduction of time lag is essential for the continued development of our subject training system, which has yielded results, but has certain limitations in the areas of response time and false feedback due to artifacts. We are presently investigating a Lock-in Amplifier System (LAS) to overcome these system limitations. Frequency and phase facile system capabilities as well as artifact rejection techniques are being developed for the LAS. This powerful tool should enable effective training by continuously supplying subjects with an indication of their EEG output at a reference frequency. The experimental/prototype system will be discussed.

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A REAL TIME FREQUENCY ANALYSIS METHODOLOGY FOR EVOKED POTENTIAL LOOP-CLOSURE

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ABSTRACT

Evoked EEG response research indicates the potential for a Usable Brain Actuated Control System (UBACS). Reduction of time lag is essential for the continued development of our subject training system, which has yielded results, but has certain limitations in the areas of response time and false feedback due to artifacts. We are presently investigating a Lock-in Amplifier System (LAS) to overcome these limitations. Frequency and phase facile system capabilities as well as artifact rejection techniques are being developed for the LAS. Improved LAS response time is projected. This powerful tool should enable effective training by continuously supplying subjects with an indication of their EEG output at a reference frequency. The experimental/ prototype system will be discussed.

1. INTRODUCTION

Response detection in the human electroencephalogram (EEG) to an evoking stimulus is obtainable when using appropriate signal averaging techniques. The sinusoidal modulation of this stimulus results in a condition referred to as a Steady State Evoked Potential (SSEP). Research in this area suggests that the SSEP may be a useful indicator for mental-state estimation (Spekreijse, 1966; Regan, 1972; Wilson and O'Donnell, 1980).

The results of this research indicate that the obtained describing functions are sensitive to changes in task loading. SSEPs were found to be unique to each individual within the general classifications of alpha and non-alpha responders. Alpha and non-alpha responders refer to the strength of the evoked response and remnant response in the alpha band (8Hz to 12Hz) compared to responses in adjacent frequency areas. SSEPs were also found to be sensitive to levels of attention, especially in the alpha band.

Although the results from this technique are promising, there is a difficulty with this and perhaps other evoked physiological measures that needs to be addressed. The visual-cortical response is an open loop measure. Unlike human performance in a manual control situation where an optimal behavior for best performance exists, the subject is not provided with an environment directing a certain response when measuring SSEPs.

In our evoked response studies no performance feedback was provided. Even with this lack of feedback or loop closure, the evoked response was found to be repeatable over a three year period (Junker et. al., 1987). It is also interesting to note that task loading often increased the evoked response and reduced variability. A result of this was that subjects were often unaware of their state of attention causing a weak or unevoked response. Based upon what was learned from our research in manual control experimentation (Levison, 1983; Levison et. al., 1971; Levison and Junker, 1978), it was concluded that a closed-loop visual-cortical response paradigm could provide an improved response. The techniques and equipment assembled to achieve this loop closure are addressed in this report.

2. BACKGROUND

2.1 Analog v.s. Digital Approach To Feedback

If any feedback loop is to be effective it must also contain minimal lags and transport delays. A system for VER loop closure with a reasonably narrow

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(0.5 cps) frequency specificity might well be diluted in its utility if an excessive phase lag (time delay) is present. To simultaneously achieve a small delay and frequency specificity is not an easy task. For the work reported above (Junker et. al., 1987), a frequency specificity of 0.0244 Hz was achieved, but only by analyzing 40.96 seconds of data at a time. It was concluded that concurrent frequency resolution and timeliness could not be achieved by our available digital system. From manual control results it is known that human controllers can more efficiently compensate for lags in a system than pure time delays (such as would exist in a digital system) by deriving lead through extraction of rate and acceleration information from sensory displays. To obtain specific frequency information from an EEG, however, requires some method of frequency averaging to extract the signal from the noise. Knowing this, and based upon manual control results, it was decided to investigate an analog active-filter rather than a digital computer approach. In this way delays in the system produced by signal averaging would be principally transfer lags instead of pure time delays.

2.2 Lock-in Amplifier

The active-filter approach consists of using a Lock-in Amplifier System (LAS) for obtaining continuous information about a subject's VER. The LAS can be extremely sensitive in detecting periodic signals of low amplitude and poor signal to noise ratio. The LAS equivalent response is that of a very sharply tuned band-pass filter. Other researchers have made use of LAS technology for measuring frequency responsiveness of the human EEG in an open loop context (Kaufman and Price, 1967; Regan and Cartwright, 1970; Hileman and Dick, 1971; Euler and Kiessling 1980; Nelson et. al., 1984). The LAS consists of two quadrature phase sensitive detectors, the outputs of which are lowpass filtered and converted to polar form to yield continuous gain and phase measures of the subject's VER at a selected reference frequency. Lock-in amplifiers have the ability to recover a clean signal from very high level noise. Generally a low frequency signal is modulated by a carrier at a known frequency, the carrier being generated within the system. The lock-in amplifier is switched through its two states of gain (inverting or non-inverting) by the modulating signal. A synchronously demodulated or rectified signal is obtained, provided that the modulating signal and LAS are "locked" or synchronized, and the modulating signal frequency is high enough to preclude distortion of the signal being processed.

The LAS under development at AAMRL (Figure 2.1) does not make use of a modulating carrier per se. To explain the nature of the modulating carrier used in the present system a brief discussion of steady state evoked potential, as it is being used here, is in order. When a human subject is presented with a sinusoidally modulated photic stimulation, a potential voltage can be recovered from the scalp, which is related to the stimulus. This EEG information is called a visually evoked response, or VER. The photic stimulation is, in effect, the carrier modulation of the LAS.

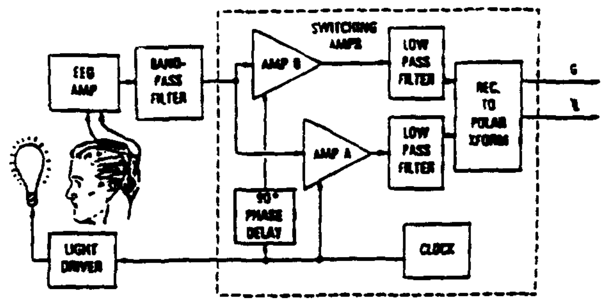

Figure 2.1. Lock-in Amplifier System.

Human EEG often appears to be noise, yet the information contained in it can be resolved with bandpass filtering. The LAS behaves like a narrow bandpass filter, and additionally is phase sensitive. To render the LAS non phase-dependent and simultaneously extract phase information, two amplifiers are operated in quadrature and the resulting signal is low pass filtered to derive a "DC" value (refer to Figure 2.1). This value is then applied to a real time analog circuit which performs a rectangular to polar computation. The information output is in the form of one voltage indicating the phase relationship of the EEG to the reference clock which switches the amplifiers and a second voltage indicating the amplitude or gain of the EEG component at the reference frequency. This is a generally accepted engineering procedure for lock-in amplifier implementation. The delay in the system is almost entirely due to the delay inherent in the low pass filters between the switching amplifiers and the X-Y to polar converter. The frequency resolution of the system is related to the Low-Pass Filter (LPF) cutoff frequency and the sharpness of the filter attenuation. The trade-off is time delay versus resolution.

2.3 Feedback Training System

The possibility of realizing a Usable Brain Activated Control System (UBACS) rests on being able to "decode" EEG or finding a method to train persons to configure EEG change in some detectable manner. Recent investigations conducted at AAMRL/HEG indicate conscious control of VER is possible, provided a suitable training environment and system is established. Eight out of eight subjects were able to demonstrate conscious control of VER after twelve hours of training. The training setup presently in use allows a subject to receive an indication of the EEG component at the reference frequency selected in as close to real time as can be achieved. The two main requirements that must be met, on the purely technical level are: a) frequency resolution must be sufficiently high to enable the training system to provide an accurate indication of VER change at the reference frequency, and, b) that the information be delayed as little as possible.

2.4 Frequency Resolution Of System

The frequency resolution of our present system is a window 0.5 cps wide. The curve is bell shaped with the half power or -3 dB point 0.25 cps on each side of the center frequency and 6 dB down at 0.5 cps each side of center. One can look at the degree of resolution two ways. Given an EEG information input bandwidth of 300 cps, a 0.5 cps window represents a resolution of 0.6%, this sounds good, but from a technical viewpoint it is often best to see the design features in the worst light. The 0.5 cps LAS window is "looking" through a preconditioning bandpass active filter 5.0 cps wide, this yields a resolution of 10% of the preconditioned signal.

2.5 Time Delay Of System

The time delay of the LAS depends primarily upon the frequency characteristics of the LAS lowpass filters. The extant filters are Sallen and Key type unity gain LPFs. With the lowpass filters set to 0.5 cps the 0 to 95% rise time is 1.7 seconds and the 100 to 5% fall time is 1.2 seconds. At first the LAS seems to have an unacceptable response time. However, embodied in the response time there is only an initial 0.2 second period in which there is absolutely no response followed by a transient rise or fall in the LAS response (Figure 2.2). Based on findings from manual control studies, the rate information available from the LAS with its inherent 0.2 second transport delay should still prove to be a useful feedback medium.

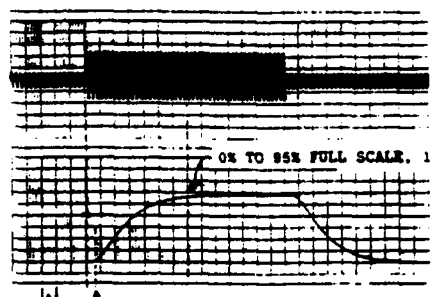

Figure 2.2. LAS time response to a 13.25 Hz sinewave step.

It has been shown that the human system has a rapid response to a steady state sine modulated photic input stimulus. The actual time lags involved with human VER are approximately 100 to 120 msecs for the 12 to 25 cps range and between 120 and 220 msecs for the 3 to 10 cps range (Spekreijse, 1966). These times depend on a number of factors for steady state VER including depth of modulation, mental state, and degree of illumination (Spekreijse et. al., 1977). Based on an estimated figure of 100 msec delay, it is understandable how a signal processing time of 200 msec allowed the successful training of eight subjects.

2.6 Artifacts

An EEG broadband response has been recorded in some subjects, notably those with prior mental discipline training such as meditational practices. With certain subjects, when instructed to attempt to increase VER, the entire EEG band under examination increased significantly. This type of increase in EEG has been observed in more than one subject. Since the object of this training is to enable persons to consciously control the VER, as is needed for a first step to realizing a UBACS, this type of response must be relegated to the artifact category. A type of broadband emission that appeared to be of the same type was also observed in one subject who tensed muscles in an attempt to fulfill the training requirement. This was determined to be a muscle artifact emission. A useful system for investigation and the training of subjects for VER control must provide a means for discrimination against the above mentioned signal contaminations.

3 . CURRENT EFFORT

3.1 Three Channel Lock-in Amplifier

A new LAS is presently under construction which should allow more effective training and investigation of VER control. The new system employs three Lock-In-Amplifier core assemblies similar to the one in use now and is called LAS-3 (Figure 3.1). The LAS-3 system performs FFT in as close to real time as practicable, in three frequency slots 0.5 cps wide, simultaneously. All three of these FFT analysers can be individually controlled or all can be operated in a tracking mode. The outputs of the three LAS cores undergo real time artifact rejection computation, the results of which operate the visual and aural VER indicators.

3.2 Master Clock

Much of the operation of the LAS-3 depends on the master reference clock. This timing reference can resolve 0.001 cps from 0.001 to 99.999 cps and is based on digital/analog Phase Locked Loop (PLL) technology, as distinguished from an all digital PLL. The core reference of this PLL is a highly stable 10 cps square wave. A conventional digital frequency divider network is used to place the output of the PLL anywhere between 0.001 and 99.999 cps.

This frequency, 7.0 cps, for example, is set to the Frequency to be Examined (FE). The FE and a 90 degree quadrature FE are used to control two Lock-in Amplifiers. They are FE-X and FE-Y, or simply X and Y. This LAS core and its associated X-Y to Polar converter and LPFs is called Center as it is bracketed by the two remaining cores which are designated Outer High and Outer Low, or O-H and O-L. Each core has its own quadrature generation and PLL circuitry, X-Y to Polar converter and LPFs, to form complete LAS units.

One primary difference between the Center, O-L and O-H, is the center derives its core reference from the master clock at 10 cps while the outer LAS units derive their core reference frequency from FE. An example LAS-3 configuration could be as follows: Center FE is set at 7.0 cps, this frequency now becomes core reference for O-L and O-H, the O-L PLL digital frequency divider is then set to operate at 6.5 cps and the O-H divider is operated at 7.5 cps.

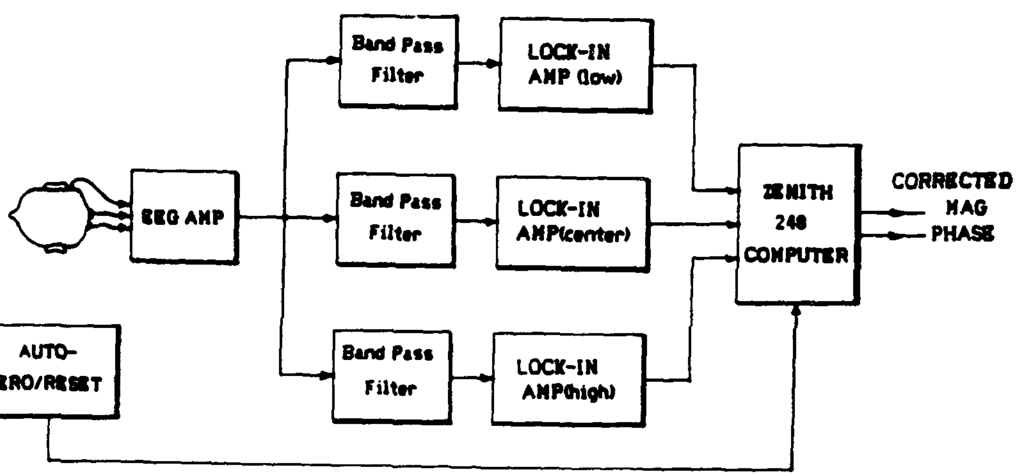

Figure 3.1. Three channel lock-in amplifier system.

3.3 Phase Shifting Flexibility

The center LAS core generates a time locked sine wave that is phase stable with FE and at the same frequency. This signal is used to drive the photic stimulation lamp. Also generated by Center is a time locked sine wave in the audible range. This circuitry is also operated by an A/D PLL with a digital divider network and is referenced to the master clock. The low distortion sine wave used for driving the photic stimulation lamp is passed through an analog delay line (ADL). This ADL is of the charge transfer or charge coupled "bucket-brigade" device type, and is clock controlled. The ADL allows the experimenter to shift the phase of the stimulation signal enabling the signal to be placed anywhere from 0 to 359 degrees phase relative to the master or reference clock , as well as additional "wrap-around" delay of up to four seconds. This makes possible phase step and phase rate of change determinations of the LAS-3 and of the human "black box" system being investigated. Phase adjustments can be easily implemented in real time by simply altering the ADL clock frequency, in standard operation, the stimulation and master clock are 0 degrees phase relative.

3.4 Frequency Shifting Flexibility

The LAS-3 Center or guide channel is provided with an "analog" frequency change feature. The control voltage operating the oscillator of the PLL is normally derived from a phase comparison of reference and frequency division selection which is defined by a digital word. This control loop can be interrupted, and a direct current from another source can then be used to determine the operating frequency of the entire system, as opposed to a digital word defining the operating frequency. This allows a number of variations of system operation to be implemented. A tracking mode guided by the processed outputs of one or more of the LAS-3 channels is only one option available in the analog mode. Another immediately useful variation on the standard operation is an electrically isolated (for safety) control potentiometer placed in the training environment allowing the subject to select an operating frequency. This frequency is then measured and recorded. Finally, the digital word for that frequency is entered into the systems control, and the stable "platform" of the PLL reinstated.

3.5 Low Pass Filter Design

The speed and resolution of the LAS-3 is determined by the characteristics of the low pass filters in the X-Y to Polar converter signal path and the pre-conditioning filters applied to the EEG information. The pre-conditioning filters can, if properly designed, enhance system speed and resolution to a degree. In the LAS-3 these filters are of the standard band pass type and remain largely unchanged and do not contribute a great deal to system loss in speed. The significant advance in speed and frequency resolution of the new system is the contribution of an unconventional design low pass filter. In place of a previous filter with a -90 degrees phase lag at 0.5 Hz, the new filters present a phase lag of -80 degrees, with the following important differences: attenuation at 0.5 cps is -10 dBV as opposed to -6 dBV, the transport delay is decreased to 100 msec from 200 msec. The net result is frequency resolution of 0.3 Hz or nearly twice the specificity and the halving of the delay of information throughput.

3.6 Artifact Rejection

The LAS-3, due to three channels of simultaneous real time FFT, has the ability to discriminate against both muscle artifact and the mentally generated broadband EEG response exhibited by some subjects. This discrimination is accomplished by programs executed by either digital and/or analog computation that prevent the subject from receiving loop closure data if the EEG information appears on all three LAS channels at once, as it would during a broadband response. Since the type of training being conducted is aimed at allowing a subject an opportunity to practice conscious, frequency specific control of their EEG, only narrow band responses will be acknowledged as valid data and be allowed to generate a return stimulus.

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